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FRACTURE MECHANICS CHARACTERIZATION OF WELDS: FATIGUE LIFE ANALYSIS OF NOTCHES AT WELDS; J_{Ic} FRACTURE TOUGHNESS TESTS FOR WELD METAL

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13. ABSTRACT *(Maximum 200 words)*

In this report two methods of fracture analysis of welds will be emphasized, one addressing fatigue life testing and analysis of notches at welds, and the other addressing the final fracture of the welded component and the fracture toughness tests used to characterize final fracture. These fatigue and fracture methods will be described by referring to recent work from the technical literature and from the U.S. Army Armament Research, Development, and Engineering Center, primarily fracture case study and fracture test method development investigations. A brief general summary will be given of fatigue and fracture methods and concepts that have application to welded structures. Specific fatigue crack initiation tests and analysis methods will be presented, using example results from a welded stainless steel box beam of a cannon carriage. Recent improvements and simplifications in J-integral fracture toughness tests will be described, particularly those related to welds. Fracture toughness measurements for various stainless steel weld metals and heat treatments will also be described.

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INTRODUCTION

Traditionally, heavy section steel castings and forgings have been used for the cannon components and cannon support structures in armament systems. It is only in the last decade that welded structures have been used in armament to any significant extent, in response to requirements for reduced weight. Therefore, the use of fatigue and fracture test and analysis methods for welds in armament components is relatively new and is based on the more general methods developed for metal structures in various applications.

FATIGUE AND FRACTURE METHODS FOR WELDS

Methods for analysis of cracking at welds can be grouped into one broad category if a significant notch is always present. This is not always true, but it may be for most serious cracking problems at welds. In the somewhat limited application of welds to armament discussed in the introduction, it has been true that weld cracking problems are notch-related. This allows us to group the methods of fatigue and fracture analysis of welds into three related types, each with a notch or crack already present, as shown schematically in Figure 1. A summary of the three types of analysis is given next.

The stress versus life, S-N, approach for fatigue life analysis has been broadly and successfully applied to all types of structures and materials. Barsom and Rolfe (ref 1) have shown that the S-N approach works well in low and medium strength steel components with notches. They used the description of the stress at the notch root, in terms of stress intensity factor, K, and root radius, r, to describe the initiation life of a variety of structure and material combinations (see Figure 2). By normalizing the notch root stress with the material yield strength, a consistent description of initiation life is possible for a wide range of materials and specimen or structure configurations. As always with welds, the formulation for notch root stress should include the effect of any residual stress, in addition to the effect of applied stress. The present author and coworkers (ref 2) have used a notch fatigue life approach to describe the initiation fatigue life in high strength stainless steel welds. Details will be forthcoming. The notch fatigue life concept is believed to be generally applicable to welded structures that have a notch significant enough to be the source of fatigue crack initiation.

Fatigue crack propagation can make up an important portion of overall fatigue life of any structure subjected to load cycles. However, a weld can have such a severe notch or load level that, once the crack has initiated and grown to the initial size suitable for fatigue crack growth tests or analysis, nearly all the fatigue life is spent. This is often the case with welds in armament, so fatigue crack growth will be only briefly discussed. Referring again to Figure 1, the propagation life at a weld can be described using the well-known Paris expression and its integrated form. Simple examples are shown. The measured fatigue crack growth rate, da/dN, is in terms of a material constant and the stress intensity range, ΔK, to a power, n, often close to 3. For $n = 3$ the growth life, N_{GROW}, has a $1/\sqrt{a_i}$ singularity, where a_i is the initial crack size, so a_i must be determined with care. Also note that the applied (and

residual) stress, ΔS, and the factor f that relates ΔK to ΔS are raised to the Paris exponent, so they must be determined with care as well. Because of difficulties in determining the initial crack size and the effective combination of applied and residual stress, caution is advised in the use of Paris fatigue crack growth analysis in life calculations for welds.

The final failure of a weld with a crack can be characterized and predicted from measurements of fracture toughness. Welds seldom have the combination of large size and high material strength required for the measurement of plane-strain fracture toughness, K_{Ic}, so an elastic-plastic test is required, such as the J-integral fracture toughness test (ref 3). A J-integral test of one specimen can give both J_{Ic}, from which K_{Ic} can easily be approximated, and the J-R curve, which is a measure of stable crack growth beyond the J_{Ic} point. This is possible because crack growth measurements can be made at any point of the test using the unloading compliance method. If there is unstable cracking due to cleavage during the J-integral test, an abrupt drop in the load, P, versus crack-mouth displacement, V, curve characterizes the unstable cracking, as shown in Figure 1. The three-point bend test configuration is particularly suitable for J-integral fracture tests of welds, because it is simple to test and improvements in analysis have been made recently, as described below.

NOTCH FATIGUE LIFE

$K/\sqrt{r}$ Concept

The important bit of mechanics for using notch fatigue life tests and analysis in characterizing welds (and other applications) is the $K/\sqrt{r}$ concept, that is, the relationship between applied K, notch root radius, r, and the maximum stress at the notch root, S_{ROOT} (see Figure 2). The relationship is (ref 4)

$$S_{ROOT} = (2/\sqrt{\pi})\ K/\sqrt{r} \tag{1}$$

Equation (1) is exact only in the limit as $r \rightarrow 0$, but it has been found to work well for $r > 0$ as well. Barsom and Rolfe (ref 1) give examples of the use of the $K/\sqrt{r}$ concept.

The important point is that $K/\sqrt{r}$ provides a fundamental connection between the notch root stress that controls fatigue cracking and the loading and configuration of the fatigue test sample, such as that shown in Figure 2. The loading is described by the applied stress ($S_{APPLIED}$ in the familiar example shown in Figure 2), and the notch configuration is characterized by its length (or depth), a, and the root radius, r. Since S_{ROOT} accounts for the loading and configuration of the actual test specimen or component, it gives a good description of crack initiation life. It also can describe the growth life to some extent, that is, the portion of crack growth that occurs relatively close to the notch root.

The $K/\sqrt{r}$ analysis can account for differences in yield strength by using an S-N plot with S_{ROOT} normalized by the yield strengths of the various materials. For alloys of the same

type, such as the various precipitation-hardening stainless steels in forthcoming results, a single trend line on an S-N plot gives a good description for a range of yield strengths.

Box Beam Results

A recent example of notch fatigue life analysis of a welded structure using the $K/\sqrt{r}$ concept was the investigation of the fatigue failure of a cannon carriage (ref 2). The main structure of the carriage is a precipitation-hardening stainless steel welded box beam with 3-mm nominal plate thickness, shown schematically in Figure 3. Cannon firing loads produced tensile stress due to bending on the bottom plate of the beam, with the tension at an angle of about 90° to a stiffener-to-bottom plate weld. The plate and weld materials were UK specification 95-15, 16 percent chromium, 5.5 percent nickel and 95-14, 14 percent chromium, 5.5 percent nickel steels, respectively. Partial penetration welds resulted in two notches formed by the gaps between the stiffener plate and the slot in the bottom plate. A fatigue crack typically grew from the root of the deeper of the notches and eventually resulted in complete collapse of the beam.

The application of the $K/\sqrt{r}$ method to the box beam required the calculation of the applied K in bending for the configuration of the stiffener-to-bottom plate weld, including the two notches. The finite element model used for the calculation is shown in Figure 4. Half of a typical weld connection was modeled, using the usual symmetry rationale. The applied K was also determined for bending of a simple rectangular beam (ref 4) with the same notch depth, a, and total depth, W. Both sets of applied K results are listed in Figure 4, where M is applied moment and B is thickness. Even though there are two notches in the weld configuration and a varying depth, the results for the weld configuration are relatively close to those for the simple beam. The applied K for the weld with two cracks is only about 10 percent higher than that for the beam with one crack. It may be that the differences between the weld configuration and the beam counteracted one another.

Typical weld configurations, as shown in Figure 4, were made from 3-mm thick 95-15 and 95-14 materials, tested in bending fatigue and analyzed using $K/\sqrt{r}$ analysis and the finite element calculations of K. The results are shown in the S-N plot of Figure 5. A crack grown along the full 3-mm thick notch root defined the initiation life. Three-point bend specimens of the configuration shown in Figure 2 were also made and tested of the 95-15 plate, the 95-14 weld metal, and of similar (U.S. specification) 15-5 PH plate and the associated 15-500 weld metal. These results are compared with the typical weld configuration tests in Figure 5. All of the test samples had the prescribed solution treatment, air cool, and aging heat treatment, as shown in Table 1. Although there is some scatter in the results, particularly the typical weld results because of their more variable notch configuration, there is generally a single trend line for all the results. This indicates that the material strength differences (in Table 1) were accounted for by normalizing with S_{YIELD}, and the specimen configuration and root radius differences were accounted for by the $K/\sqrt{r}$ concept. This combination of S-N and $K/\sqrt{r}$ analyses of notch fatigue life at a weld is thereby shown to be a useful approach. A power law trend line of the type shown in Figure 5 can be used to make estimates of notch

fatigue life for test or component configurations with this type of material and for which K, r, and S_{YIELD} are known.

Table 1. Summary of Heat Treatment and Yield Strength of Various Precipitation-Hardening Stainless Steel Plates and Weld Metals

Material	Condition	Yield Strength (MPa)
95-15 Plate	Treat, Age at 530°C	980
95-14 Weld	Weld, Treat, Age at 530°C	1230
15-5 Plate	Treat, Age at 593°C	1100
15-500 Weld	Weld, Treat, Age at 593°C	1200

One other point may be of interest regarding the form and values of the trend line equation in Figure 5

$$N_{INIT} = 85{,}000\ [\{(2/\sqrt{\pi})\ K/\sqrt{r}\}/S_{YIELD}]^{-5.7} \tag{2}$$

The constant value of life, 85,000 cycles, that gave a logarithmic regression best fit to the data, also describes the life below which the notch root stresses are above the yield strength of the material. Note that for $N_{INIT} < 85{,}000$, the ratio $(S_{ROOT}/S_{YIELD}) > 1$. This life value at which $(S_{ROOT}/S_{YIELD}) = 1$ may be a useful and fundamental way to rate a given material (in a given environment) for its resistance to fatigue cracking at a notch.

J-INTEGRAL FRACTURE TOUGHNESS

Improved J-Integral Test Analysis

The various J-integral fracture toughness test procedures have broad application (ref 3), but they are also quite complex. Their complexity may be a particular problem for application to welds, because fracture toughness specimens from welds are often smaller than those from other material forms due to the typically small weld metal volume. A specimen of mixed weld metal and base material makeup will present problems also, as will be addressed in a forthcoming discussion.

Efforts have been made (ref 3) to simplify and improve the J-integral fracture toughness test procedure, including some recent work by the present author and coworkers (refs 5,6). The results of some of these efforts that have application to welds will be discussed next.

Referring to Figure 6, a sketch of the three-point bend configuration for J-integral fracture tests, note the two types of displacement measurement: the load-line displacement, δ; and the crack-mouth opening displacement, V. V is the easier to measure, using the proven clip-gage methods, but δ is also needed to calculate applied J. Recently (ref 5), it was shown that a simple relationship between V and δ existed for a wide range of Ramberg-Osgood power law strain-hardening materials (see Figure 7). The elastic relationship for V/δ is easily obtained from a fracture mechanics handbook (ref 4). The plastic relationship for V/δ can be obtained as suggested by Wu et al. (ref 7), who used the early elastic-plastic calculations of Kumar et al. (ref 8). More recent calculations by Kirk and Dodds (ref 9) are believed to be more accurate than the Kumar et al. results, so they were used to obtain the plastic V/δ relationship shown in Figure 7. Note that the results are not very sensitive to the Ramberg-Osgood strain-hardening exponent, n. By including the shallow and deep crack limits for V/δ, an expression for all crack depths was developed for plastic V/δ

$$(V/\delta)_{PLASTIC} = 1.384(a/W) - 1.497(a/W)^2 + 2.339(a/W)^3 - 1.226(a/W)^4 \tag{3}$$

Equation 3 was fitted to results for $n = 20$, but also fits quite well for $5 < n < 50$, which includes nearly all structural alloys. The importance of Equation 3 is that J-integral fracture tests can now be performed with the bend specimen using only the easy-to-measure V and the existing test procedures. For weld tests, with their associated complexities, this is a useful simplification.

The effect of crack-starter notch thickness on specimen compliance has been investigated (ref 6) and found to be significant. Figure 8 shows the results of calculations of load-line compliance for the bend specimen and the differences in compliance for different starter notch thicknesses. Compared to the compliance for an ideal zero-thickness notch (or crack) (ref 10), a notch with $t/W = 0.1$ has a 14 percent higher compliance at $a/W = 0.6$, for example. The user of J-integral tests, particularly the unloading compliance aspects of the tests, had best be aware of the effect of notch thickness. If a notch with $t/W = 0.01$ is used, such as that produced by electric-discharge machining, the compliance is close enough to the ideal to be of no bother.

A concern with J-integral tests of welds was recently raised by Eripret and coworkers (ref 11). They advised caution in using standard J-integral fracture test methods for welds, because the plastic displacements measured in some material-configuration combinations may not be those associated with crack growth. Consideration of the Reference 11 work has led to the following comparison of the compact and three-point bend specimen configurations for use in J-integral tests of welds (see Figure 9). The compact specimen has loading arms that deform and loading holes in close proximity to the crack mouth where displacement is measured. These features can lead to unwanted displacements being included in the total V measurement with a weld present, particularly for small a/W and for overmatched welds, that is, for higher strength in the weld than the base material. Rather than V being a measure of the elastic and plastic deformation in the weld ahead of the crack, as intended, it also includes deformation of the arms made up predominantly of base material. In contrast, the bend

specimen has greatly extended arms that deform very little, so V is primarily a measure of deformation in the weld ahead of the crack, as it should be. This significant difference in the two specimen configurations makes the bend specimen a far better choice for J-integral fracture toughness tests of welds.

One final point regarding improved J-integral test methods relates to the scatter of the J versus Δa data used to determine J-integral fracture toughness. The zero point of the J-Δa data and the toughness measured from the data can each be affected by scatter, particularly so with weld tests for reasons already discussed. A method to be sure that the lower portion of the J-Δa data is unaffected by scatter, and matches the calculated blunting line as required by J-integral concepts, is summarized in Figure 10 (ref 5). A Δa shift is applied to the data points so that there is zero average deviation of the data from the lower part of the blunting line, using the following method:

$$\Delta a_{SHIFT} = SUM_i\,[\Delta a_i - (J_i/2\sigma_F)]/i$$
$$\text{for } 0.2\ J_{Ic} < J_i < 0.6\ J_{Ic} \qquad (4)$$

where Δa_i and J_i are the data used for the shift calculations (see example in Figure 10) and σ_F is the flow stress (the average of the yield and ultimate tensile strengths). Careful application of the standard J_{Ic} test method (ref 12) should eliminate the need for shifts much larger than that shown in Figure 10. Nevertheless, the zero-shift method will significantly lessen the effect of data scatter on J-integral fracture toughness measurements for welds and other applications.

Stainless Steel Results

Example J-integral fracture toughness results for the type of stainless steel used in the cannon carriage are shown in Figures 11 and 12. The load-displacement plot shown in Figure 11 is typical of welds with heat treatments to be avoided. The shortcut of skipping the solution treatment after repair welding, for example, has a significant price. Unstable cracking caused by cleavage occurred with the welded and aged 15-500 material and caused the abrupt load drop. Note that the unstable cracking caused a noticeable increase in the unloading compliance, which indicates a significant crack advance. A similar result was noted for welded and aged 17-400 material (U.S. specification), compared in Figure 12 with other results from stainless steel welds with more beneficial heat treatments. This comparison shows the applied J versus Δa data from which J_{Ic} is calculated, for the various weld materials and heat treatments. Table 2 lists the key results. Note that even the as-welded condition for 17-400 gives a significant improvement in J_{Ic} compared to the weld and age treatment. As expected, the complete heat treatment gives the highest J_{Ic}. Note further that a simple representation of the J-R curve for these three conditions of 17-400, that is, the J at 1 mm of crack growth, shows even more clearly the difficulty of the shortcut heat treatment and the advantage of the proper treatment.

Table 2. **J-Integral Fracture Toughness Results for Precipitation-Hardening Stainless Steel Welds**

Material	Condition	Yield Strength (MPa)	J_{Ic} (KN/m)	J: Δa = 1mm (KN/m)
17-400	Weld, 593°C Age	1280	75	75
17-400	As-Welded	1280	100	180
17-400	Weld, Solution Treat, 593°C Age	1140	140	210
95-14	Weld, Solution Treat, 530°C Age	1230	90	130

The example J-integral fracture toughness results in Figure 12 and Table 2 also show a comparison of J-integral fracture toughness for two alloys, 17-400 and 95-14, each in its prescribed solution treat and age condition. The 17-400 has the higher toughness, and the 95-14 has the higher strength. For some weld applications, a higher toughness may be required. For others, a higher strength may be desired.

In general, J-integral fracture toughness tests provide broadly useful graphic and quantitative measures of the crack growth resistance of welds, whether the concern is with unstable fracture (K_{Ic}), the initiation of stable crack growth (J_{Ic}), or a significant amount of stable growth (J-R).

SUMMARY

Two methods of fracture test and analysis of welds have been described, one addressing fatigue life testing and analysis of notches at welds, and the other addressing the J-integral fracture toughness tests used to characterize final fracture of welds. Fatigue crack initiation tests and analysis and J-integral fracture toughness measurements were presented, based on a case study of a welded stainless steel box beam of a cannon carriage. Recent improvements and simplifications in J-integral fracture toughness tests for use with welds were discussed. Key advantages and limitations of the two types of fracture test for welds can be summarized as follows.

Key Features of $K/\sqrt{r}$ S-N Analysis for Welds

The quantity $K/\sqrt{r}$ relates directly to the stress at a notch root in a weld, and it can be defined by the loading and configuration of the weld. $K/\sqrt{r}$ used as the stress in the usual S-N fatigue approach gives a good description of crack initiation fatigue lives of welded components.

$K/\sqrt{r}$ analysis can account for differences in yield strength by using an S-N plot with $K/\sqrt{r}$ normalized by material yield strength. For alloys of the same type, a single trend line on an S-N plot gives a good fatigue life description for a range of yield strengths.

The $K/\sqrt{r}$ method also identifies the fatigue life below which the notch root stress is above the yield strength of the material, which may be a useful way to compare materials for their resistance to fatigue cracking at a notch.

The $K/\sqrt{r}$ method can describe the fatigue crack growth life only to a limited extent, that is, only for that portion of crack growth that occurs relatively close to the notch root.

Key Features of J-Integral Tests for Welds

A J-integral test of a single weld specimen can give both J_{Ic}, from which K_{Ic} can be easily approximated, and the J-R curve, which is a measure of stable crack growth beyond the J_{Ic} point. This is possible because crack growth measurements can be made at any point of the J-integral test using the unloading compliance method.

Unstable cracking due to cleavage during a J-integral test of a weld is clearly identified by an abrupt drop in the load-displacement curve and as low J_{Ic} values and J-R curves, compared to the J values expected for stable cracking.

The three-point bend test is particularly suitable for J-integral fracture tests of welds, because it is inherently simpler to fabricate and load and a recent improvement in analysis has made its test procedure as simple as that of the compact specimen. A new relationship between load-line and crack-mouth plastic displacements allows tests using only crack-mouth displacement measurements, with load-line displacements simply calculated.

The three-point bend configuration has an inherent advantage for J-integral tests of overmatched welds, where displacements non-local to the crack can cause errors. Errors that can occur with the compact specimen - related to the loading arms and the loading points - are less likely to occur with the bend specimen, because the comparable locations are at lower stress levels in the bend specimen.

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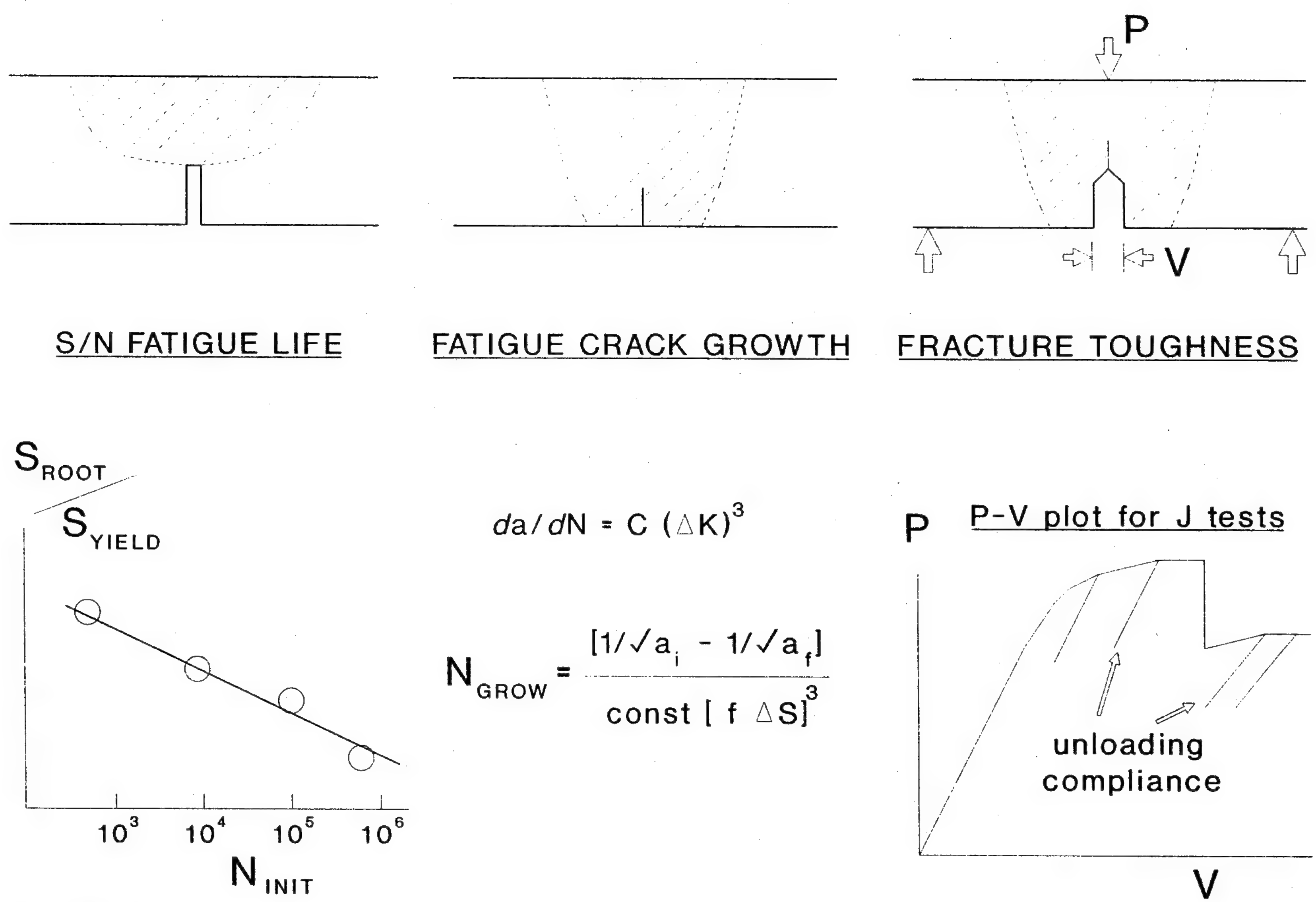
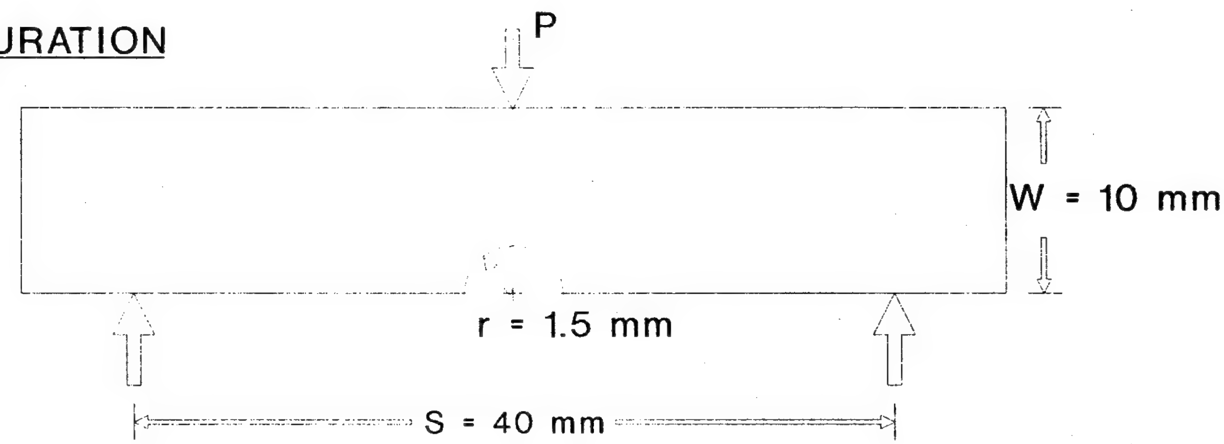
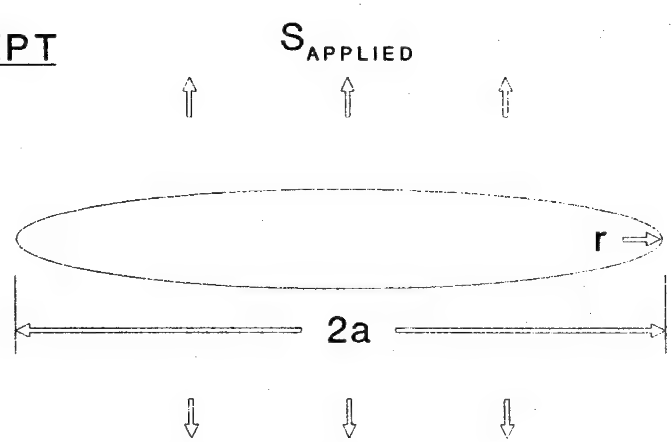


FIGURE 1
Fatigue and Fracture Mechanics
Test and Analysis Methods for Welds

TEST CONFIGURATION



K/√r CONCEPT



$$S_{ROOT} = (2/\sqrt{\pi})\, K/\sqrt{r}$$

$$K = S_{APPLIED} \sqrt{\pi a}$$

$$N_{INIT} = \textit{function}[\, S_{ROOT} / S_{YIELD} \,]$$

FIGURE 2
Notch fatigue life test configuration and K/√r S/N fatigue life concept

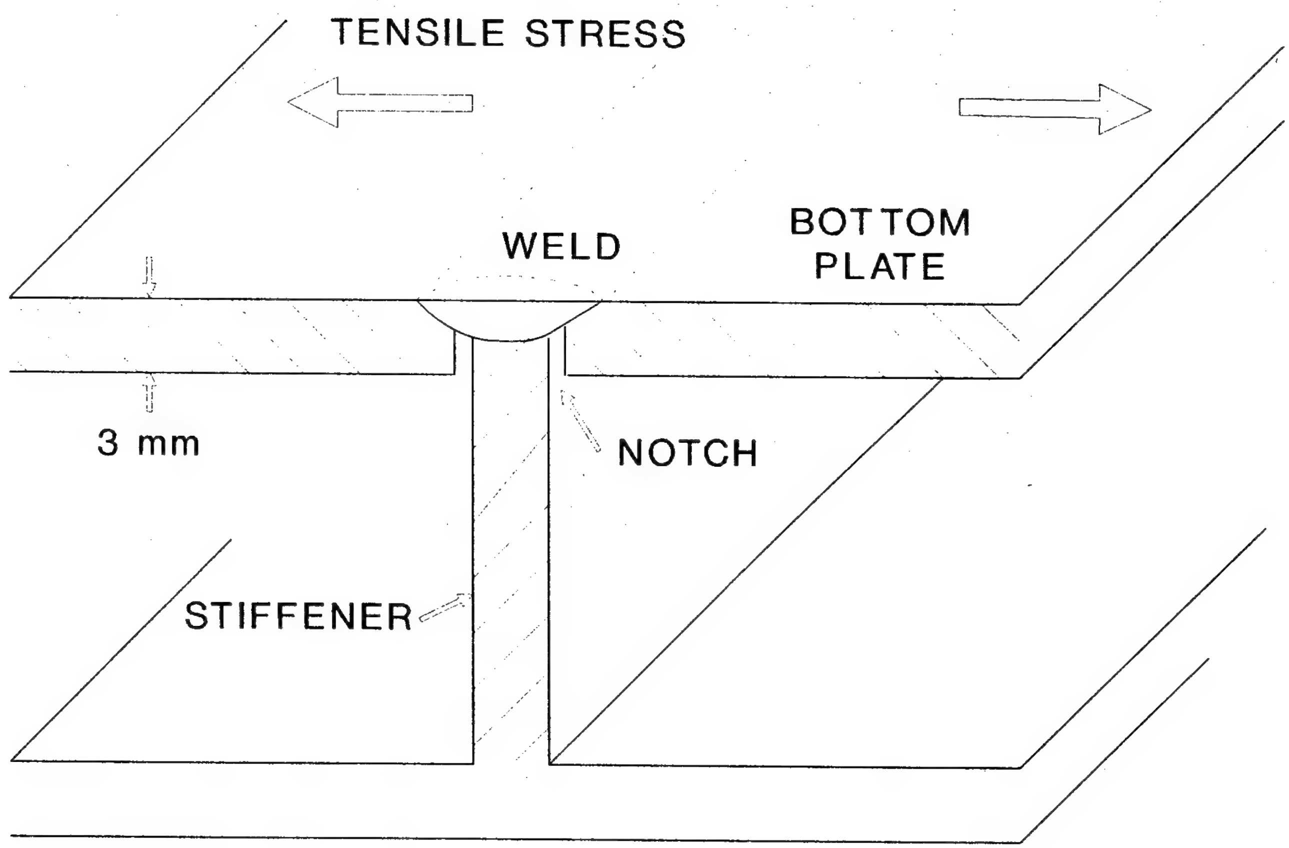
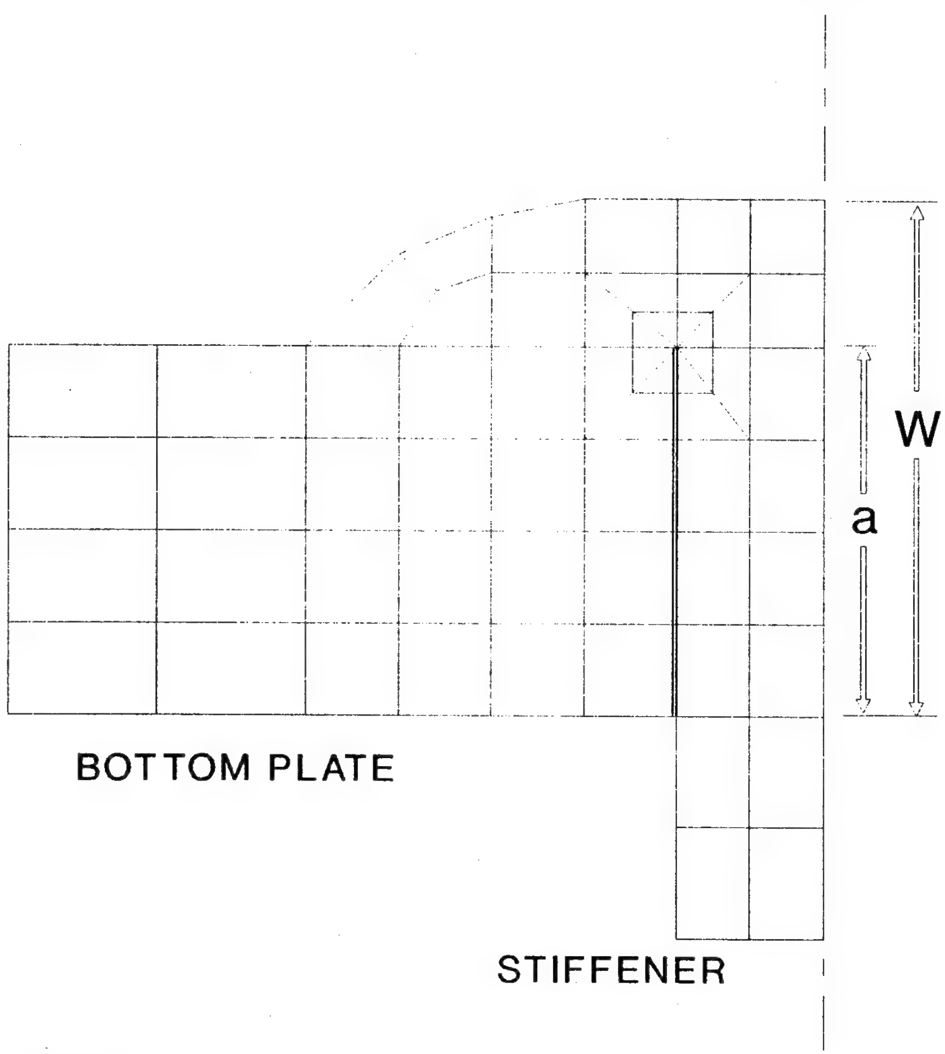


FIGURE 3
Box beam with partial penetration weld and associated notches



$[KBW^{3/2}/M]$ FOR WELD

a/W	FINITE ELEMENT *two cracks*	SIMPLE BEAM *one crack*
0.098	3.7	3.4
0.196	5.1	4.6
0.295	6.6	6.0
0.393	8.4	7.8
0.491	11.2	10.4
0.589	15.8	14.5
0.688	24.1	22.0
0.786	45.8	38.9

FIGURE 4
Finite element model of stiffener-to-bottom plate weld

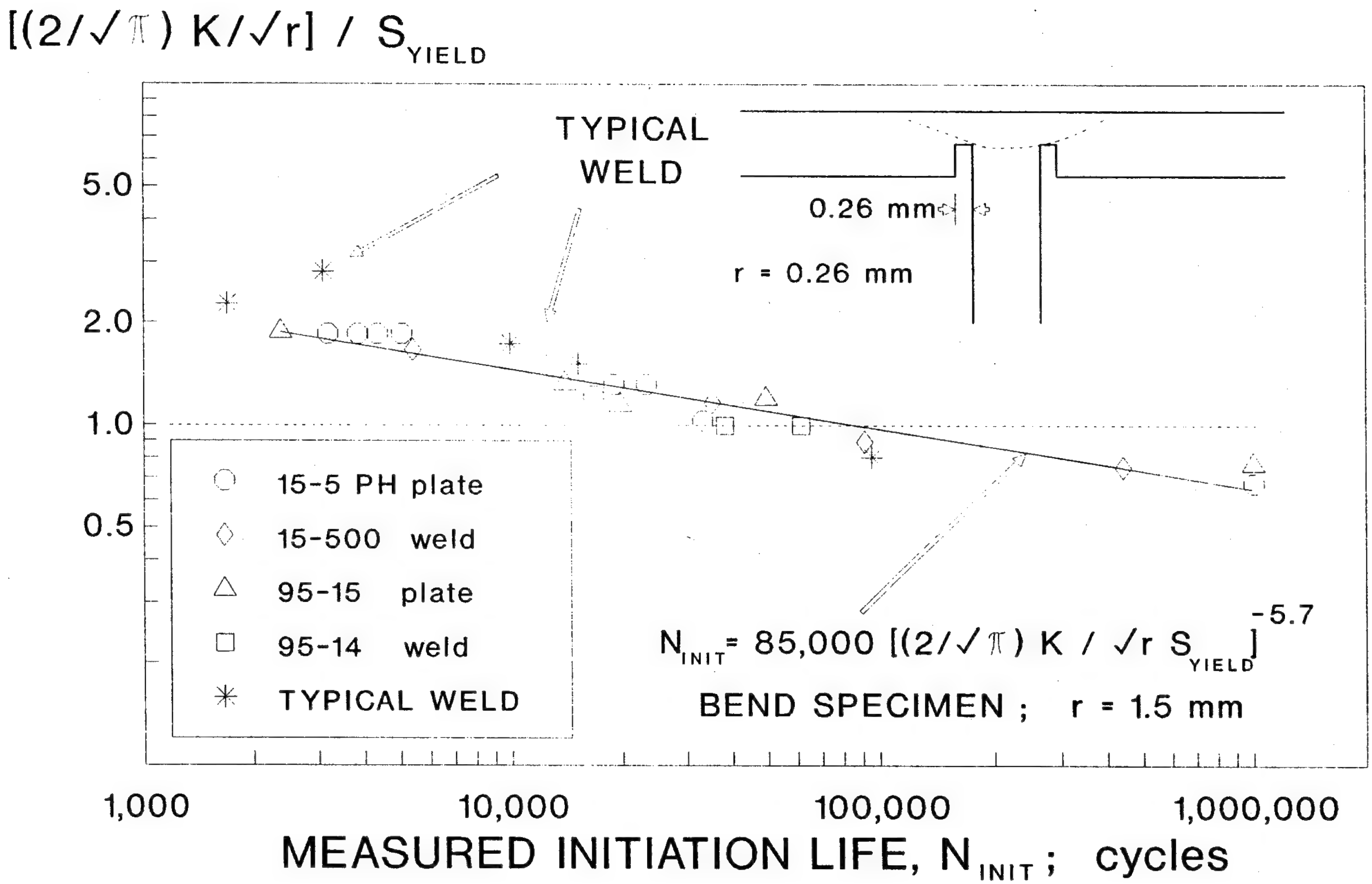


FIGURE 5
K/√r initiation life analysis for
PH stainless steel welds and plate

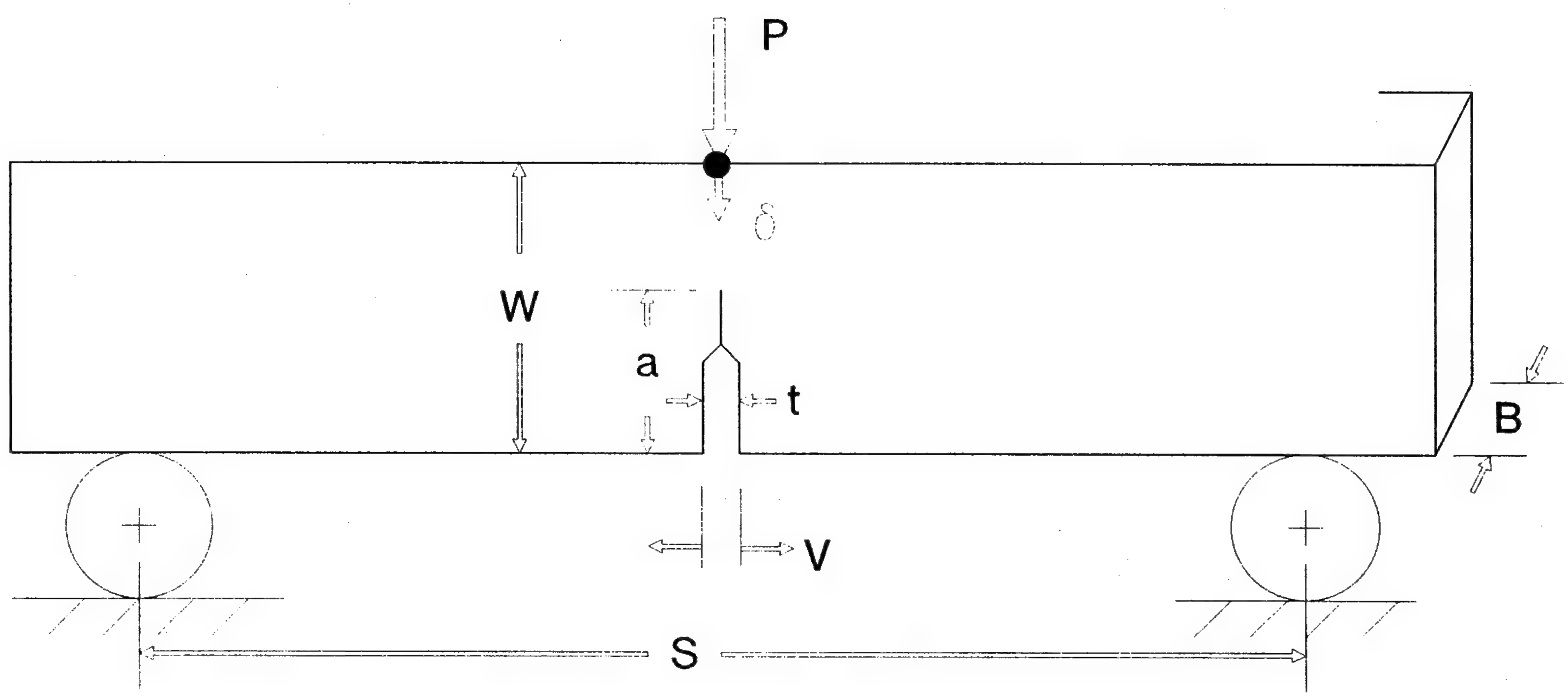


FIGURE 6
Three-point bend configuration for J-integral fracture toughness tests

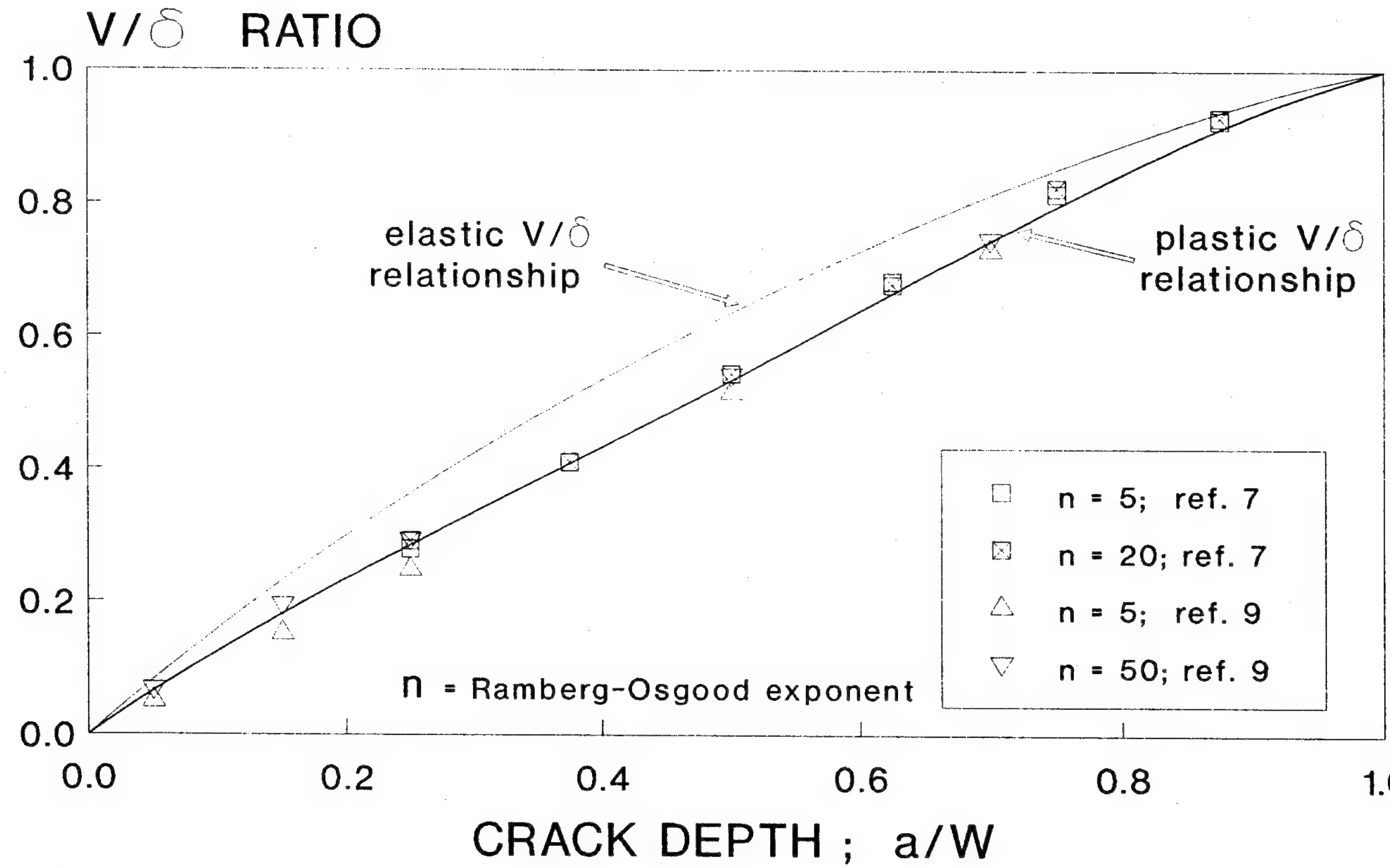


FIGURE 7
Displacement results for three-point bend specimen; elastic and plastic

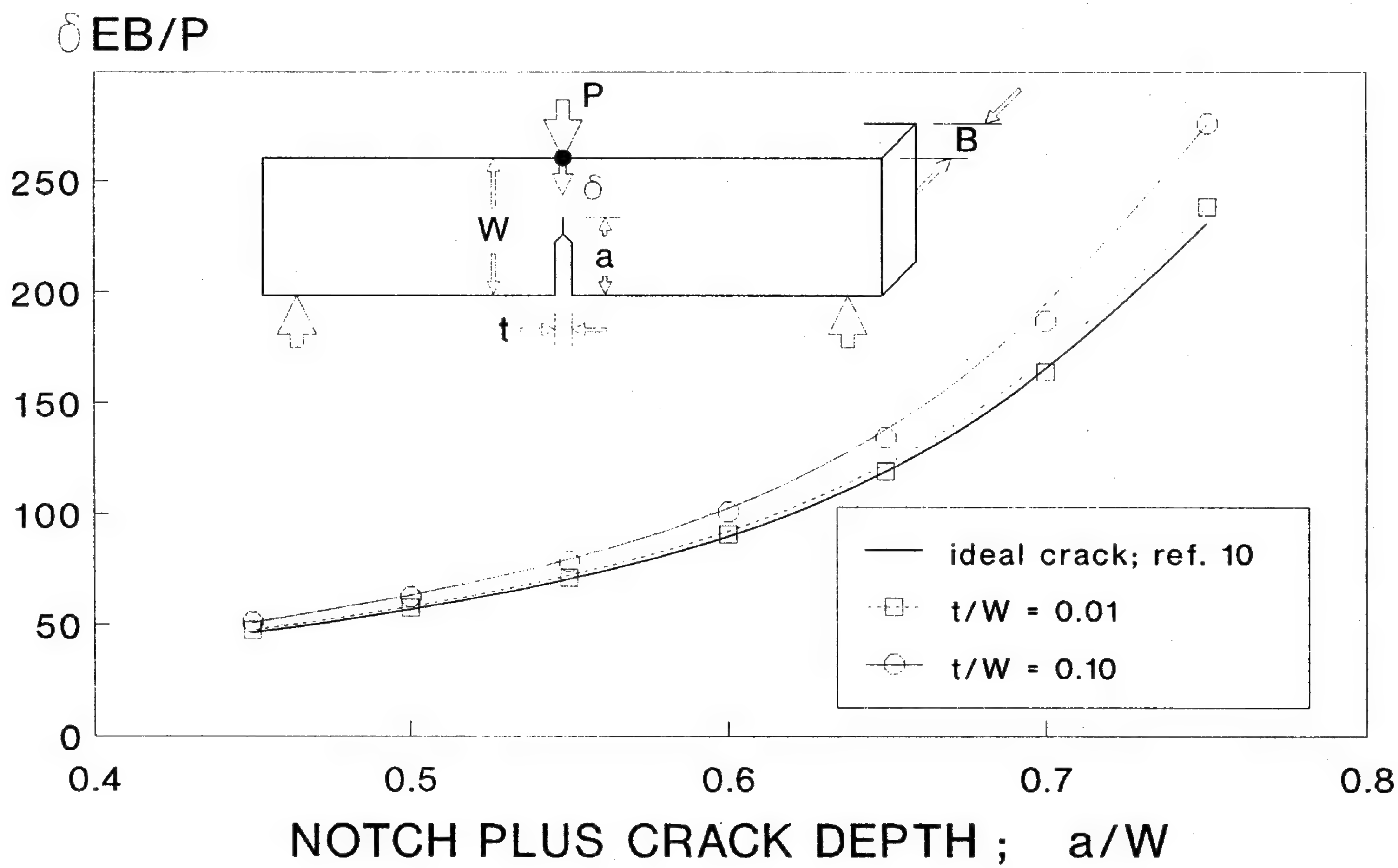


FIGURE 8
Effect of notch thickness on elastic compliance of three-point bend specimen

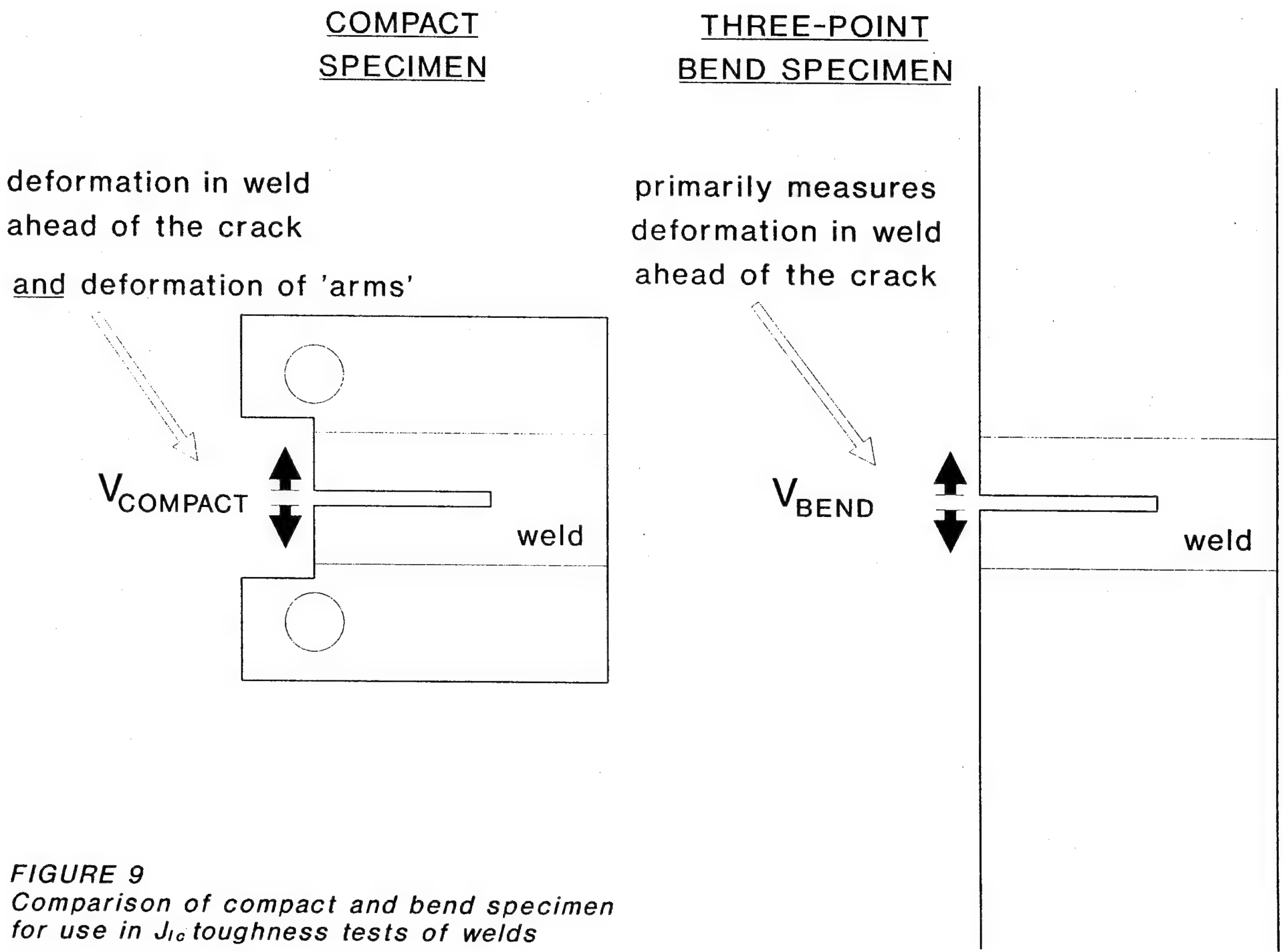


FIGURE 9
Comparison of compact and bend specimen for use in J_{Ic} toughness tests of welds

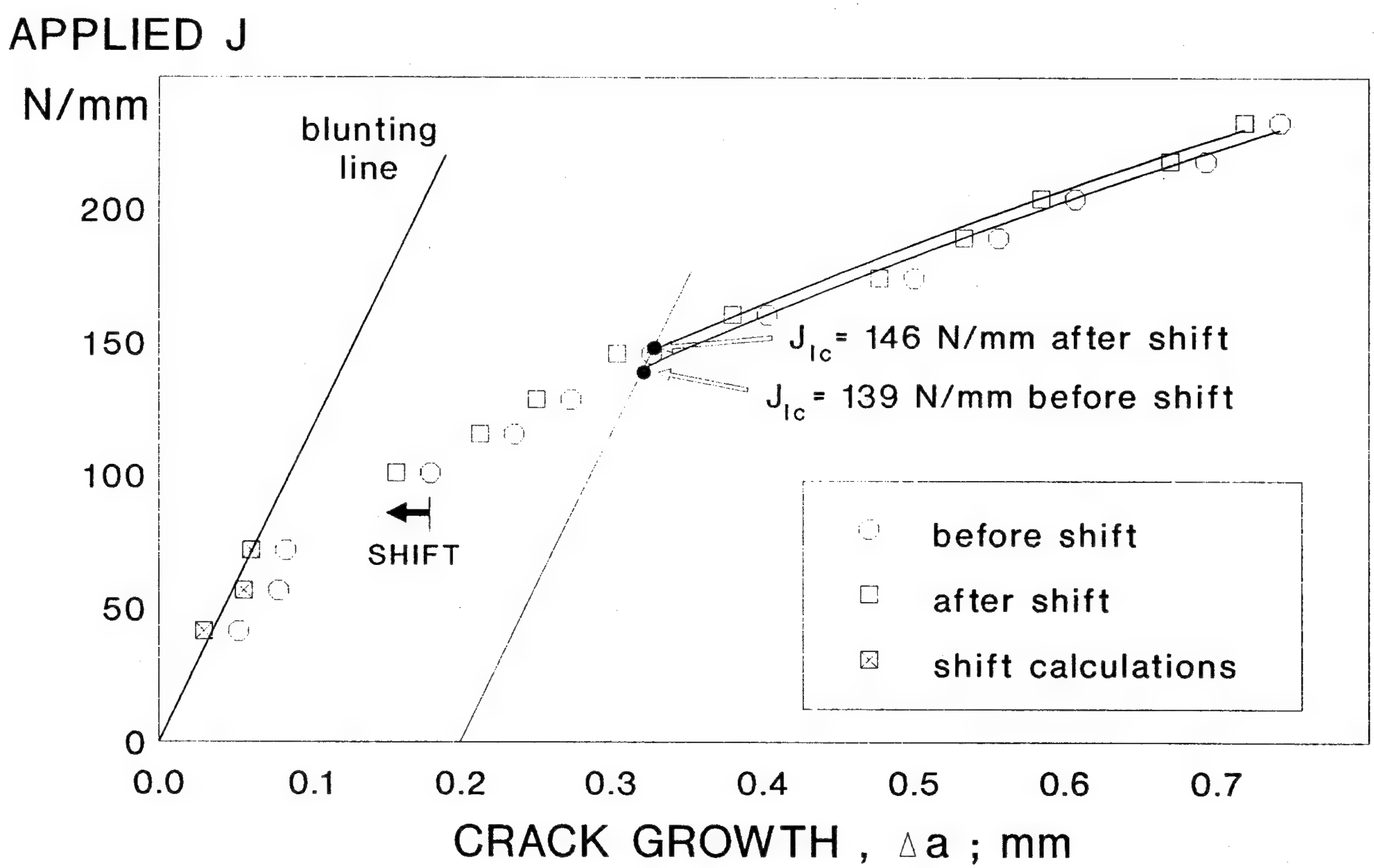


FIGURE 10
Zero Shift of Δa data for calculation of J_{Ic} for NiMn steel

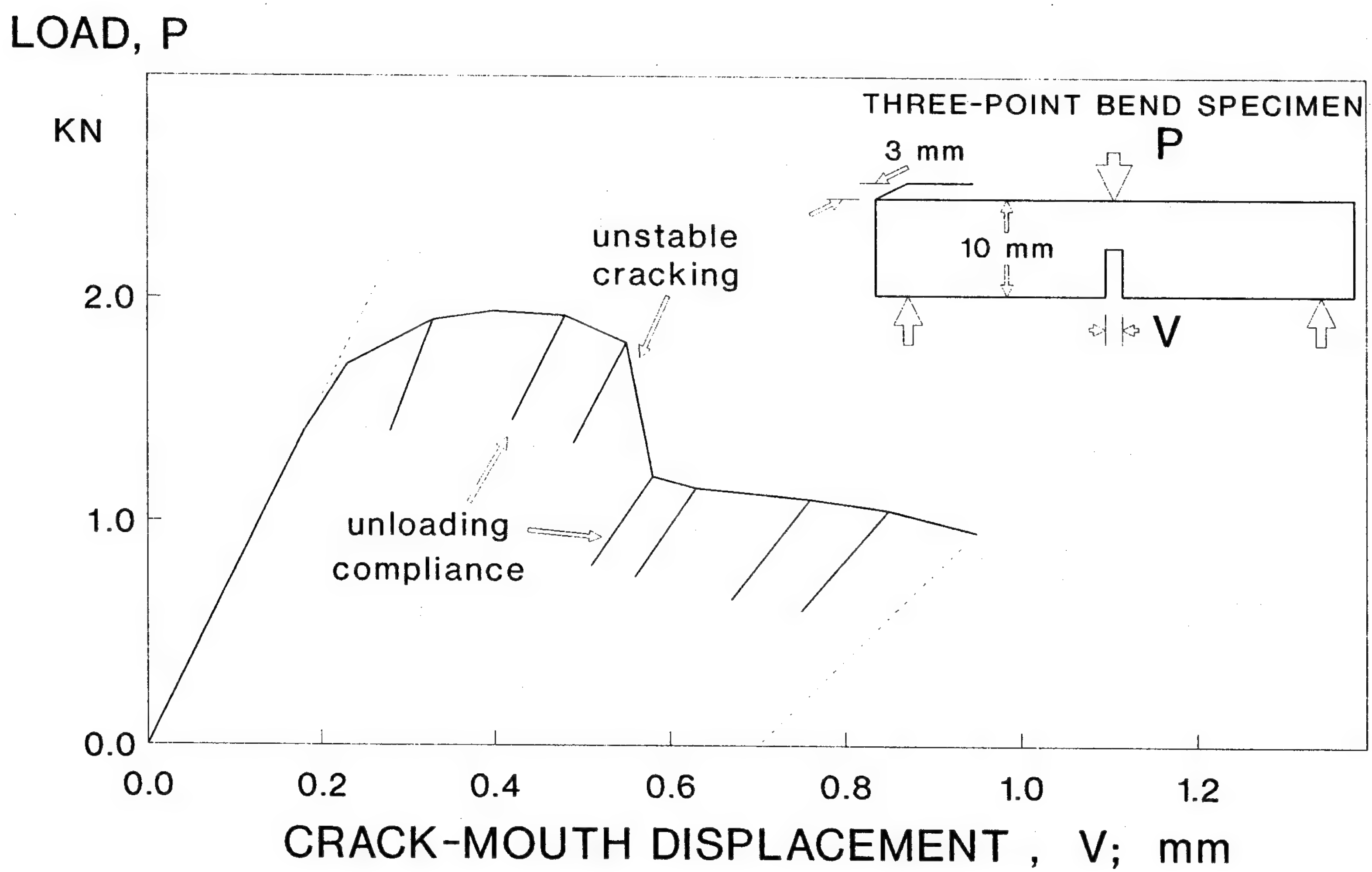


FIGURE 11
J_{Ic} test of 15-500 PH stainless steel weld; welded and aged at 593 C

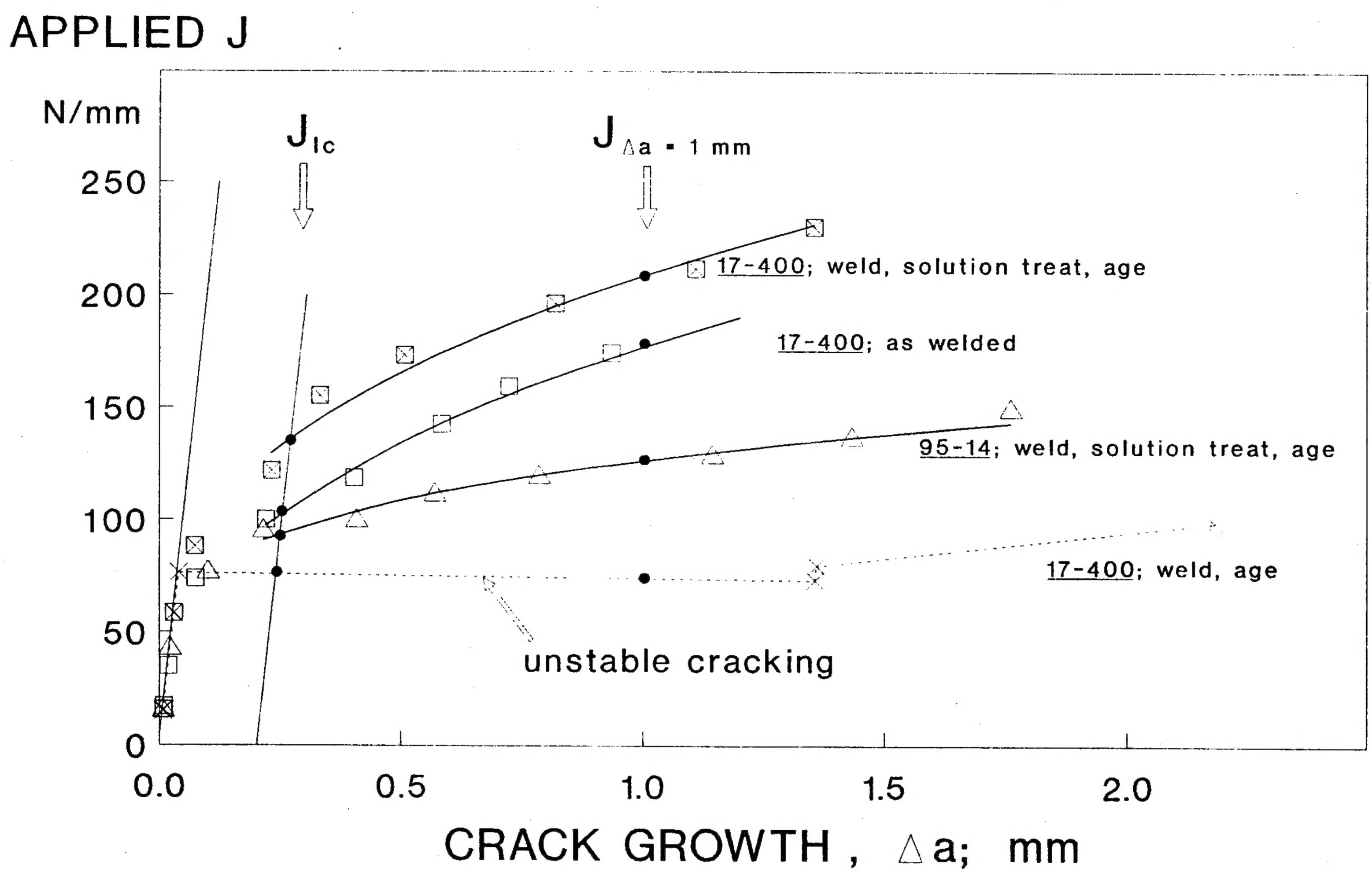


FIGURE 12
J_{Ic} tests of 17-400 and 95-14 stainless steel welds with various heat treatments

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